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Article

Analyses of Land Cover Change Trajectories Leading to Tropical Forest Loss: Illustrated for the West Kutai and Mahakam Ulu Districts, East Kalimantan, Indonesia

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Abstract: In Indonesia, land cover change for agriculture and mining is threatening tropical forests, biodiversity and ecosystem services. However, land cover change is highly dynamic and complex and varies over time and space. In this study, we combined Landsat-based land cover (change) mapping, pixel-to-pixel cross tabulations and expert knowledge to analyze land cover change and forest loss in the West Kutai and Mahakam Ulu districts in East Kalimantan from 1990–2009. We found that about one-third of the study area changed in 1990–2009 and that the different types of land cover changes in the study area increased and involved more diverse and characteristic trajectories in 2000–2009, compared to 1990–2000. Degradation to more open forest types was dominant, and forest was mostly lost due to trajectories that involved deforestation to grasslands and shrubs (~17%), and to a lesser extent due to trajectories from forest to mining and agriculture (11%). Trajectories from forest to small-scale mixed cropland and smallholder rubber occurred more frequently than trajectories to large-scale oil palm or pulpwood plantations; however, the latter increased over time. About 11% of total land cover change involved multiple-step trajectories and thus “intermediate” land cover types. The combined trajectory analysis in this paper thus contributes to a more comprehensive analysis of land cover change and the drivers of forest loss, which is essential to improve future land cover projections and to support spatial planning.

Keywords: land use change; land cover change; tropical forests; deforestation; agriculture; oil palm; Indonesia; Kalimantan

1. Introduction

Land developments for agriculture and mining in tropical forest landscapes have a strong negative impact on forests, biodiversity and ecosystem services, where they cause a decline in carbon stocks, the provision of food and the resilience of livelihoods of local communities [1–4]. This also holds for Indonesia, which is considered to be in the initial stages of a large-scale forest transition (e.g., [5–7]), with overall high deforestation rates (e.g., ~0.84 Mha of primary forest was lost in 2012 [8]). However,

large regional differences between districts and provinces have been observed [9–11]. The main drivers of forest loss in Indonesia are considered to be large-scale fires and logging activities [12–15] and the pulpwood, palm oil and mining industries (e.g., [1,16–20]). The aforementioned studies have analyzed and visualized land cover change patterns and processes at the scale of larger regions and nations, including, for example, deforestation, forest degradation and conversion to other land covers and uses. Land cover change is, however, highly variable at the local scale, because of the high geographical variability in biophysical environments, socio-economic activities and cultural contexts and would thus require local-scale analyses [10,21]. Additionally, the complex political and institutional context in Indonesia contributes strongly to local variations in land cover change [22,23]. For example, the governments at the district, provincial and national levels are all involved in decision-making processes with regard to land use allocation, spatial planning and handing out of concession permits for land development, but can have different and contrasting interests [22]. Due to these varying local conditions and decisions, land cover change does not only vary spatially, but also temporally, and is characterized by a sequence of changes, defined as trajectories [24–29]. For instance, after forest clearance, the resulting land cover or land use is not necessarily permanent or stable, but may change over time into one or multiple subsequent land cover types (e.g., [26,28–30]). To effectively apply specific tropical forest conservation interventions in a certain area, it is important to account for both local spatial and temporal variability of land cover change and thus to analyze land cover change processes and trajectories at the local to landscape scale (e.g., [25,29,30]).

Land cover change trajectories have been analyzed at the district level in Kalimantan and Sumatra, Indonesia [17,26–28]. The main trajectories involved conversions from (a) forest to land uses that were small-scale mixed cultures for the production of rice, fruit or jungle rubber, or from (b) forest to small-scale or large-scale monocultures for palm oil and rubber production, the large-scale monocultures being stable more often than the small-scale equivalent [17,26,28]. Additionally, trajectories were identified with agroforests or small-scale rubber as an intermediate land use [26,28]. The paper of [28] qualitatively described land cover change trajectories in the former West Kutai district and presented these in a schematic overview that showed the complexity of land cover change in this area. Other studies in Kalimantan and Sumatra quantified land cover change trajectories based on pairs of land cover maps covering 10–30 years, thereby showing the relative importance of each of the trajectories [17,26,27,31]. Land cover change maps have been developed at the regional scale for Sumatra and Kalimantan to visualize processes such as deforestation or agricultural expansion [19,32,33]. The paper of [17] presented the spatial land cover changes into oil palm in Ketapang district, West Kalimantan, highlighting the impact on other land cover types.

The advantages of remote sensing data are, for example, that they cover large spatial areas, including inaccessible areas, and are considered objective. Yet, they also have disadvantages. Firstly, their resolution is often not fine enough to allow the identification of smallholder plots. In addition, the fact that clouds may cover part of the images usually requires mosaicking of these images to achieve a full cover of an area, especially in the tropics. This means that making time series with a high temporal resolution is hampered and that such mosaics do not have a consistent time stamp anymore, introducing biases in the analyses conducted on them. Finally, historical ‘ground truth’ land cover data to train and validate the image classification algorithm are often not available. Although initiatives exist to create freely available global datasets to solve this problem (e.g., [34,35]), such datasets have very generalized land cover classes (e.g., cropland), which might be good for global maps, but are not very useful for local studies. Expert knowledge and remote sensing data complement each other, because expert knowledge has limitations in extent (an expert has knowledge for ‘his/her’ region only), but not in spatial and temporal resolution, as experience is continuous. Furthermore, expert knowledge is subjective, but can identify much more diversity in terms of land cover classes (e.g., identify individual crops and management systems). Therefore, to gain more insight into the temporal and spatial variation of land cover change trajectories in support of forest conservation in tropical landscapes, an integration of the abovementioned analytical steps is needed. Such an integrated trajectory analysis would

incorporate the quantification, schematic presentation and mapping of land cover change trajectories and processes over time using both remotely-sensed maps and expert knowledge. This would allow one to acquire a better understanding of the land cover change processes that are underlying forest loss, forest degradation and changes in food production in tropical regions.

In the current study, we aim to present an integrated approach, combining land cover (change) map analyses and expert knowledge to characterize, quantify and map land cover change processes and trajectories that have contributed to forest loss, forest degradation and displacement of mixed croplands at the local to landscape scale. Following this approach, targeted interventions in the landscape can be prioritized and developed. We selected the resource-rich districts of West Kutai and Mahakam Ulu, in the Indonesian province of East Kalimantan, because we expected a high occurrence of land cover change driven by land development, the exploitation of natural resources and large-scale fires [28,36–38]. We conducted pixel-to-pixel analyses of land cover change processes and trajectories using locally-acquired Landsat-based land cover maps for the years 1990, 2000 and 2009, to analyze local spatial and temporal processes and trajectories. Land cover change studies at the pixel level have proven useful to define which land cover types were replaced by which other types over a certain timescale (e.g., [1,16–20]). Additionally, we quantified, schematically presented and mapped the stepwise land cover changes, thereby operationalizing the land cover change trajectories that had been defined for the study area in a qualitative way by [28]. We used detailed land cover classes in the analyses of the land cover change processes and trajectories, in order to be able to disentangle processes such as forest degradation, forest regeneration and land use intensification, as well as the land cover types involved in such processes. The integrated approach presented in this paper and its outcomes can assist in the modelling of future land cover change at the local to landscape scale and in focusing forest conservation interventions on specific frontier areas of land cover change.

2. Materials and Methods

2.1. Case Study Region

We analyzed the West Kutai and Mahakam Ulu districts as a single area because the data originate from the period before the division into two districts in 2012. The districts have a total land area of ~3.3 Mha or ~33,000 km² and are located in the western part of East Kalimantan (Figure 1 and Figure S2 in Supplementary Materials), which is a remote and isolated area due to minimal infrastructure. Nonetheless, West Kutai and Mahakam Ulu are very attractive areas for widespread agricultural expansion and the extraction of timber, coal and gold due to the potential for land development in the lowland areas and the presence of natural resources [39]. Between 2010 and 2017, the total population in Kutai Barat and Mahakam Ulu increased by ~4% from 165,918–173,303 inhabitants [39], with a substantially higher population in Kutai Barat, which is located at lower altitudes and closer to East Kalimantan's capital Samarinda, and therefore more easily accessible by road and river. The rate of immigration is unknown. The indigenous Dayak communities used to practice small-scale shifting cultivation [28]. The traditional rotation cropping made land cover change in the past cyclical and gave space to forest regeneration [24]. The authors of [40] found that inhabitants of the more remote settlements in the north-eastern part of Kalimantan depended more on gathering and selling of (forest) products, while the less remote villages acquired an income through agriculture, such as rice, traditional rubber and rattan [40]. Nowadays, the production of rice, vegetables and fruit for household use and rubber and rattan through traditional rubber and rattan gardens is increasingly being integrated into or replaced by the larger scale and commercialized production of rubber and palm oil, as well as the extraction of timber, coal and gold [28].

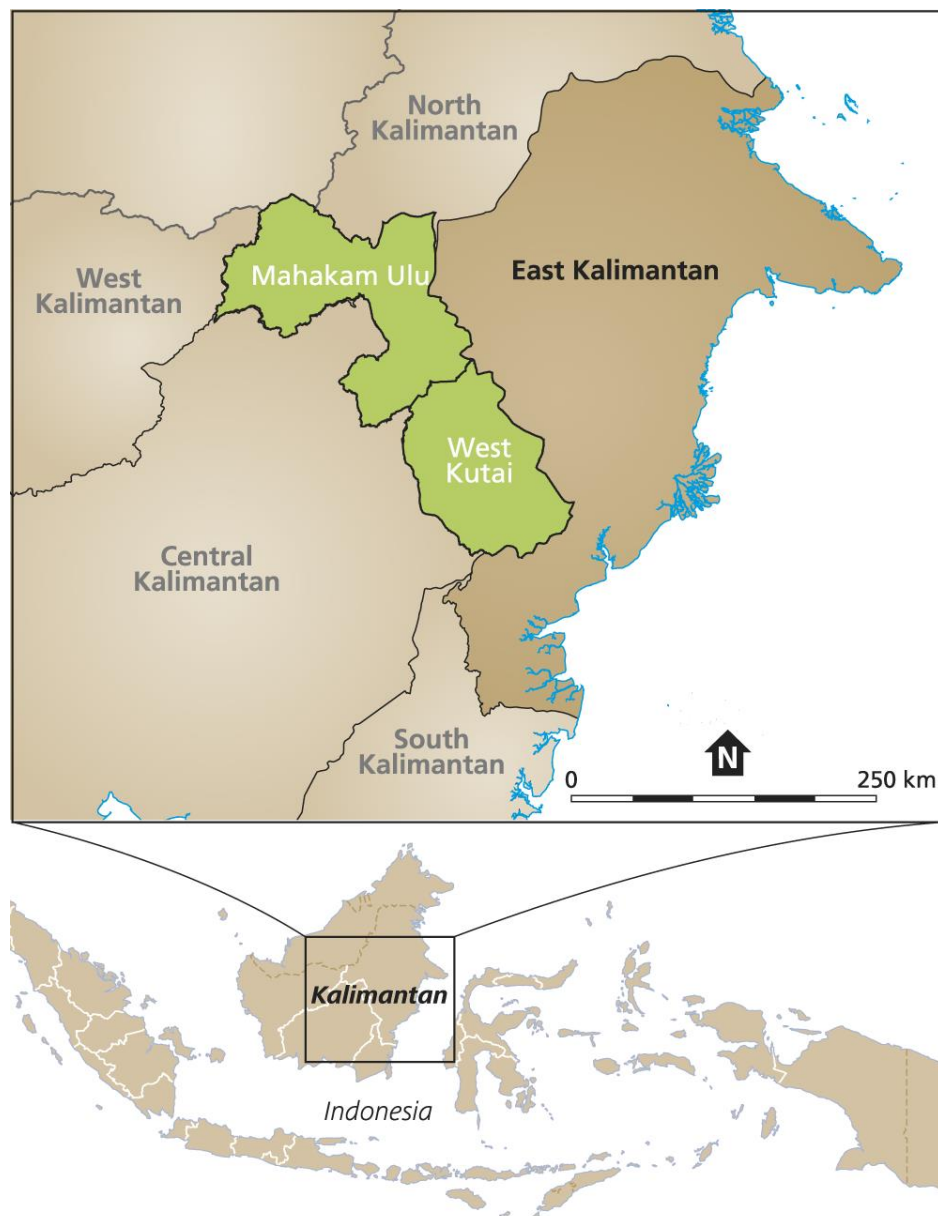


Figure 1. Map of the West Kutai and Mahakam Ulu districts, province of East Kalimantan, Indonesia.

2.1.1. Social, Economic and Political Context

Indonesia has a turbulent social, economic and political history. Government-sponsored transmigration schemes and spontaneous migration from the inner to the outer islands of Indonesia have resulted in widespread agricultural development in Sumatra and Kalimantan [16,41]. After the economic crisis and resignation of Suharto in 1998, Indonesia has been in a transition period from a centralized system of governance towards a more open and liberal socio-political environment, known as Reformasi [36,41]. Reformasi involved rapid formal and informal decentralization processes that were driven mostly by decisions made by provincial and district-level actors who found that the benefits from natural resources and agriculture flowed out of their regions to the national government and the private sector [36]. Prior to Reformasi, forests were under the control of the central government, and Indonesia had an overcapacity in the wood processing industries, resulting in high deforestation rates. During Reformasi, the Indonesian government reformed the forestry sector, with attempts of more just and equitable benefits of forest resource management between governments, the private

sector and local communities [42]. Meanwhile, district and provincial governments have received greater benefits from the development of agriculture and mining in their jurisdictions, which is contributing to large-scale developments of agriculture and mining in certain provinces and districts (see Figure S3B for logging, timber and oil palm concessions planned in the area).

2.1.2. Land Allocation Zoning

In Indonesia, land is divided into so-called land allocation zones consisting of forest zones and non-forest zones. According to the 1983 Forest Land Use Planning by Consensus (Tata Guna Hutan Kesepakatan (TGHK)), the forest zone has been categorized as the production forest zone (Hutan Produksi (HP)), limited production forest zone (Hutan Produksi Terbatas (HPT)), watershed protection forest zone (Hutan Lindung (HL)), conservation forest zone (Kws. Suaka Alam dan Pelestarian Alam (KSPA)) and production forest for conversion zone (Hutan Produksi yang dapat di-Konversi (HPK)) [32]. These zones are under the jurisdiction of the Indonesian Ministry of Environment and Forestry. In the forest zones, only forest-related activities are allowed, such as forest conservation or logging. The development of estate non-tree plantations, such as oil palm plantations, is prohibited in forest zones (Figure S3A). The non-forest zone (Kawasan Budidaya Non Kehutanan (KBNK), formerly called Areal Penggunaan Lain (APL)) is designated for the development of agriculture. These land allocation zones do not necessarily represent actual forest cover, meaning forest zones exist without forest cover, while non-forest zones exist with large extents of forest [32] (see Figure S3A for a map of the land allocation zones in the study area).

2.2. Land Cover Maps and Expert Knowledge

Land cover maps for the years 1990, 2000 and 2009 were developed by automatic unsupervised classification combined with manual digitation of a time series of 30-m resolution Landsat TM/ETM-7 satellite imagery in ESRI ArcGIS (see also [43]). The land cover maps are shown in Figure S2 (in the Supplementary Materials).

To enable the analyses of the land cover change processes and trajectories, we classified land cover types in great detail. The land cover classes included three forest types representing different degradation levels, namely closed canopy, medium open canopy and very open canopy forest. Other natural vegetation types were shrubland and grassland. For the agricultural land cover types, we distinguished between small-scale and large-scale agriculture, including mixed cropland and smallholder rubber gardens as small-scale land uses and rubber plantation, pulpwood plantation and oil palm plantation as large-scale land uses. Furthermore, we classified cleared land, gold mining, coal mining, settlements and water (see further Figure S2 and Table S1).

The forest types used manual interpretation based on the crown cover (CC) percentage, texture and signs of infrastructure. The CC refers to the canopy closure or tree density within a pixel or uniform forest polygon. Closed canopy forest (high density, CC > 70%) appeared as a dark green color with a coarse texture on the 5-4-2 bands of the Landsat images and included pristine forests, as well as post-logging regrowth with fast-growing tree species. Medium canopy forest (medium density, CC = 40–70%) had a color and texture similar to the closed canopy forest type, but showed signs of degradation by the presence of bare soil (pink or red color), networks of logging roads, gaps, log yards and ponds and base camps. Open canopy forest (low density, CC = 10–40%) showed more recent logging activities and the emergence of shrubland. Shrubland is a vegetation type that arises after land clearing and may include a few remaining natural trees (<5 m high). Grassland included cleared land and occurred in dry and swampy areas. This land cover type has a grey to green color on Landsat-5 TM Bands 5-4-2 due to flooding. Large-scale plantations showed regular straight boundaries and covered relatively large areas. When the plantations are young, the color of the vegetation is similar. Pulpwood (*Acacia* spp.) plantations are industrial forest plantations. Young *Acacia* (mangium) is light green in young stands and dark green in mature stands. Oil palm (*Elaeis guineensis*) plantations include large-scale estates and smallholder plantations. The color on Landsat-5 TM Bands 5-4-2 is light yellow

in young stands and light green in mature stands. Rubber (*Hevea brasiliensis*) plantations are generally planted by plantation enterprises and are therefore homogenous in tree composition. When mature, the plantation has a brownish red color. Smallholder rubber is a land use with rubber trees that are often mixed with secondary re-growth. Smallholder rubber has a reddish yellow color. Mixed cropland refers to seasonal crops, orchards and paddy fields. The seasonal crops were difficult to distinguish from recently burned area as the color on the Landsat image is similar (pink-red/reddish). We were able to identify them by assuming that the seasonal crops are commonly planted near natural forest or old secondary vegetation. Orchards were identified as these are mostly dominated by durian, coconut and mango trees and are found behind old Dayak villages. The orchards are difficult to distinguish from old secondary vegetation as the structure is similar; however, their location is close to settlements and alongside rivers and roads. Paddy fields are commonly found on alluvial plains along the edge of big rivers. Coal mining was identified based on the purple-red color on the Landsat images (5-4-2), with adjacent roads towards the river ports. To support the classification and validation of the land cover maps, we used a variety of data sources, including geotagged photos, topographic maps, floristic zone maps, soil maps, infrastructure data, survey data, focus group discussions and expert knowledge. More information on the data sources and the classification process can be found in [43].

The validation of the land cover maps by 136 field observation points, for which 136 geotagged photos of land cover that were taken in 2009 were interpreted and compared to the exact location on the 2009 map, resulted in a map accuracy of 75%. For the analyses, the land cover maps were projected to an 'equal area'-projection and rasterized at a 100-m resolution. A semi-structured expert group-consensus workshop was conducted focused on eight main questions and with eight local field experts (i.e., two team coordinators/ecologists, three ecologists, two social scientists and one policy analyst) to acquire information about the land cover changes, processes and main, often multi-stage trajectories that occurred in the study area between 2000 and 2009 (see Supplementary Materials S1 for more details about the interview). We selected a semi-structured and group-consensus approach instead of an individual knowledge-elicitation approach, as this is an open procedure, allowing new ideas to arise (see [44]). Experts were selected according to their expertise on land cover change, agricultural development and forest loss (see above for the experts' expertise). The experts were asked eight main open questions on the identification of the main land cover change processes in the study area during the period 2000–2009 (see Supplementary Materials S1 for further details about the approach, the questions and the answers). We also asked, for example, what the main initial subsequent land uses were on previously forest land, if the initial land use in a certain area remained stable or was changed into other land uses and which land uses these were. Additionally, we asked why farmers choose certain land uses and/or decided to convert to others. The aim of the expert group-consensus workshop was to create an overview and schematic model of the main land cover change trajectories in order to support the design of the land cover map analyses and to have a better understanding for what reason these had occurred since 2000 according to the perception of the interviewees. Additionally, because we applied three land cover maps, the trajectories analyzed from the maps had at most three stages per pixel. Integrating the expert knowledge and land cover map analyses, the latter gave us a quantification of each of the 'flows' (areas of change) in the schematic model.

2.3. Analyses to Quantify and Visualize Land Cover Change Processes and Trajectories

The analyses consisted of four phases to quantify and visualize the land cover change processes and trajectories (for more details on the processes and trajectories, see Supplementary Materials S2). In the first phase, we conducted a quantification and comparison of the area per land cover type for 1990, 2000 and 2009 based on the attribute tables of the land cover maps in ArcGIS 10.4.1. In this way, we could quantify what land cover types increased and what land cover types decreased in land area between 1990–2000 and 2000–2009 and during the whole time period 1990–2009. However, this part of the analysis did not allow us to quantify the land cover change processes and trajectories or to identify what land cover types had replaced the previous land cover over the time frame analyzed.

For this reason, in the second phase, we integrated the findings of the workshop with the experts with pixel-to-pixel cross tabulations of the land cover maps, in order to characterize and analyze the land cover change processes and trajectories, which we call the trajectory analyses (see for example Ekadinata and Vincent, 2011). More specifically, these trajectory analyses consisted of the following sub-phases:

- (2a) The findings from the workshop with the experts (see Supplementary Materials S1) resulted in a schematic model of the main land cover change processes and trajectories that occurred between 2000 and 2009, showing which processes and trajectories were dominant and which land cover types were intermediate and/or stable for longer periods of time.
- (2b) Subsequently, the pixel-to-pixel cross tabulations based on the land cover maps resulted in land cover change matrices with on the vertical axis the initial land cover types and on the horizontal axis the land cover types of the subsequent time step. These land cover change matrices reflect the area of change (ha) in which a one-step trajectory occurred within the selected time period, namely 1990–2000, 2000–2009 and 1990–2009. However, the three decadal land cover maps could only show trajectories with a maximum of three stages per pixel. We have therefore included expert knowledge to understand the processes between the decadal land cover maps. Subsequently, the one-step trajectories that resulted from the quantified land cover change matrices were then translated into a schematic diagram, based on the schematic diagrams that resulted from the expert workshop.

Third, as the cross tabulations were conducted on a pixel-to-pixel basis, we mapped the processes and trajectories by linking the outcomes of the pixel-to-pixel tables to the pixels of the land cover maps. Fourth, we overlaid the land cover map for 2009 and the land cover change processes map for 2000–2009 with concession and land allocation zoning data for the year 2009 (the last two data sets were only available for 2009) to analyze the differences in the occurrence of land cover types and land cover change processes across the different concession types and land allocation zones.

3. Results

3.1. Quantification of Forest Loss and Land Development

The land cover map comparisons showed that in 1990, most of the land in the West Kutai and Mahakam Ulu districts was covered with forest (~2.9 Mha; ~88%) and that about 9% of this forest area was lost between 1990 and 2009 (Figure 2, Figure S2, Table S2). Forest loss increased between 1990–2000 (~262,000 ha; ~5%) and 2000–2009 (~315,000 ha; ~4%) (Table S2). Not only the total forest area decreased, but also the qualities of the forest in terms of canopy cover. Closed canopy forests declined from 1990–2009 by ~29% to ~1.1 Mha in 2009 (Figure 2, Table S2). In contrast, medium open and very open canopy forests increased between 1990 and 2009 in terms of land area with ~14% and ~21% to ~1.1 Mha and ~0.44 Mha, respectively (Figure 2, Table S2). We observed that grasslands more than doubled in area from 1990–2009 to almost 103,000 ha (Table S2), while the shrubland area remained similar. Further, from 1990 until 2009, smallholder rubber almost tripled from ~44,000 ha to ~122,000 ha and remained the main agricultural land cover type in the region. Mixed cropland, which is considered the main land cover type for food production, increased from ~12,000 ha to ~26,000 ha. Oil palm plantation development underwent the highest increase from only ~135 ha in 1990 to ~31,000 ha in 2009 (Figure 2, Figure S2, Table S2). The total agricultural and mining area increased from ~65,000 ha in 1990 to ~222,000 ha in 2009.

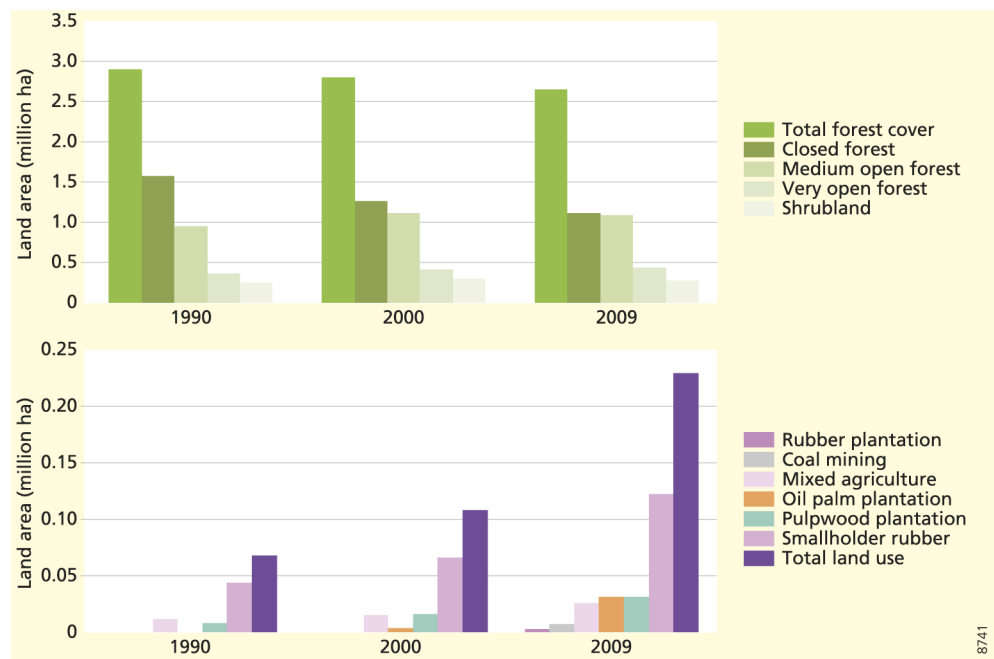


Figure 2. Land cover change in the West Kutai and Mahakam Ulu districts between 1990 and 2009, based on quantitative analyses of the land cover maps [43]. Change in natural land cover types (top graph), namely ‘total forest cover’ (summation of the three forest cover types), the forest types differentiated based on canopy closure and shrubland (grassland is excluded since it entails a relatively small land area); and change in the anthropogenic land uses (bottom graph), namely ‘total land use’ (summation of all anthropogenic land uses, excluding gold mining and settlements) and the six land uses differentiated by type. ‘Total land use’ is calculated as the sum of the six anthropogenic land use classes and shows an increase from 0.07 Mha in 1990 to 0.22 Mha in 2009. This increase of anthropogenic land use is, in most part, at the expense of the decrease of ‘total forest cover’ from roughly 2.9 Mha in 1990 to 2.7 Mha in 2009.

3.2. Trajectory Analyses

3.2.1. Land Cover Change Processes and Trajectories Identified by Experts

The main land cover change processes and trajectories in the period 2000–2009, as identified by the experts (thick arrows in Figure S4 in the Supplementary Materials show the dominant processes), were large-scale deforestation and, subsequently, conversion by concession holders and small-scale conversions of forest lands, shrublands or grasslands to mixed cropland and/or smallholder rubber. On a less common basis, regeneration occurred from grassland to shrubland and forest types.

According to the experts, land cover change has been highly dynamic in the region with land cover types rapidly succeeding each other. However, the time steps between the land cover conversions varied. The following trajectories were identified for the period 2000–2009 based on the group-consensus workshop with the experts (Figure S4) in order of complexity:

- A. One-step trajectories of degradation and/or deforestation, for example, from closed forest to very open forest (i.e., degradation) or, for example, from forest to shrublands or grasslands (i.e., deforestation);
- B. Multiple-step trajectories of (i) deforestation to grasslands and (ii) subsequently conversion from grasslands to large-scale plantations. These trajectories involved, for example, land cover changes from forest to grasslands (i.e., deforestation) and further conversions to rubber or oil palm plantations;

- C. Multiple-step trajectories of (i) forest degradation and/or deforestation and conversion to small-scale mixed croplands, (ii) conversion after 1–2 years to smallholder rubber and (iii) in certain cases, further to monocultures, mostly oil palm. The time period to convert smallholder rubber to oil palm varied locally.

According to the experts, the choice of the smallholders between maintaining their small-scale rubber production or converting their lands into oil palm plantations (Trajectory C in Figure S4) depended on the price competitiveness of rubber versus palm oil and on the presence of success stories in the village regarding oil palm cultivation. More importantly, when small-scale rubber fields were converted into oil palm plantations, some smallholders established new mixed cropland areas in newly obtained forested lands and land cover change Trajectory C was initiated again. According to the experts, cleared lands, mixed cropland and smallholder rubber were intermediate land cover types in a land cover change trajectory. Furthermore, oil palm plantations, pulpwood plantations and coal mining were perceived as stable land uses between 2000 and 2009.

3.2.2. Quantification and Schematic Presentation of Land Cover Change Processes and Trajectories

From the pixel-to-pixel cross tabulations (Table S3–Table S7 in the Supplementary Materials), we were able to quantify and characterize the specific land cover change processes and trajectories that had occurred in the area and that had resulted in forest loss (see Figure 3A,B, Table 1). Between 1990 and 2009, about one-third (~1 million hectares or Mha) of the land cover in the study area had changed (Table S8).

Figure 3A,B and Table 1 show that in the time periods 1990–2000 and 2000–2009, most of the loss of closed to very open forest was caused by degradation to forest types with a more open canopy cover, by deforestation to grasslands and shrublands and much less by direct conversions to agriculture or mining. In more detail, over the 20 years analyzed, degradation entailed ~600,000 ha or ~59% of total land cover change, deforestation to grasslands and shrubs entailed ~178,000 ha or 17%, and conversions from forest to agriculture and mining entailed ~113,000 ha or 11% (Table 1). Table S3–Table S6 show the exact hectares). For example, in the period 1990–2000, almost 276,000 ha of closed forest was degraded to medium open forest, while about 900 ha was converted from closed forest to smallholder rubber, and no conversions from closed forest to oil palm had occurred. Further, in the period 2000–2009, an additional ~142,000 ha of closed forest was degraded to medium open forest and ~5800 ha was deforested to shrubs and grasslands. In contrast, in that same period (2000–2009), a much smaller area, namely ~700 ha, was converted to smallholder rubber and ~2400 ha was converted to oil palm.

Between 1990 and 2009, about 89% of the total area of land cover change had changed through one-step trajectories (see the arrows in Figure 3A,B), meaning that land cover had changed from one land cover type to a second land cover type within the total time period analyzed. Only ~11% of the total area of land cover change had changed through two-step trajectories between 1990 and 2009, meaning land cover had changed from one type to a second type and further to a third type. The four most frequent types of two-step trajectories that had occurred in the landscape (in terms of land area, namely ~46,000 ha in total) involved forest degradation (from more closed to more open forest types) and deforestation (from forest to shrubs or grassland). The fifth most frequent type of two-step trajectories involved changes from medium open forest to shrubs (i.e., deforestation) and further to oil palm plantations (i.e., conversions) (~5000 ha in total).

Two-thirds of the conversions to oil palm between 1990 and 2009 (~20,000 ha) occurred through one-step trajectories, of which most (~15,000 ha) involved conversions from grasslands and shrubs to oil palm, and ~4000 ha involved conversions from all forest types to oil palm. The remaining one-third of the total conversions to oil palm (~11,000 ha) occurred through two-step conversions, of which most (~7000 ha) from medium/very open forest to shrubs/grassland (in 1990–2000) and further to oil palm (in 2000–2009). The two-step trajectory from very open forest to smallholder rubber and further to oil palm occurred in an area of ~230 ha.

The increase in the number of arrows in Figure 3B compared to Figure 3A clearly shows that the area and the different types of land cover changes increased and involved a more diverse set of trajectories in the period 2000–2009, compared to 1990–2000. Deforestation to grasslands and shrubs increased between 1990 and 2009 and entailed a total land area of ~92,000 ha in 1990–2000 and ~114,000 ha in 2000–2009, which is about 17% and 19% of the total land cover change area in these time periods, respectively. However, degradation decreased from ~366,000 ha or 68% of the total land cover change in the period 1990–2000 to ~305,000 ha or 50% in 2000–2009. Conversion from forest to agriculture and mining increased from ~31,000 ha or 6% in 1990–2000 to ~70,000 ha or 11% between these two time periods. Other types of land cover change processes can be found in Table 1. Direct conversions from forest types to small-scale agriculture, such as mixed cropland and smallholder rubber, occurred more frequently than conversions to large-scale monocultures, such as oil palm or pulpwood (Figure 3A; Table S3). After 2000, however, the number of conversions to large-scale monocultures, for example oil palm and pulpwood plantations, increased substantially (Figure 3B; Table S5).

In addition to the findings of the expert workshop, the quantifications based on the land cover maps also showed that the intermediate land cover types included the more open forest types, shrubland, grassland and mixed cropland. Stable land cover types were oil palm plantations, pulpwood plantations, mining and settlements; the word ‘stable’, in this context, means that these land cover types have replaced other land cover types, but have not been replaced by other land cover types during the time periods analyzed. In other words, stable land cover types are the ones at the end of the trajectory. Interestingly, smallholder rubber was a stable land cover type in the period 1990–2000; however, it was both an intermediate and a stable land cover type in the period 2000–2009, when this land cover type was also converted into rubber, oil palm and pulpwood plantations, coal mining sites and settlements.

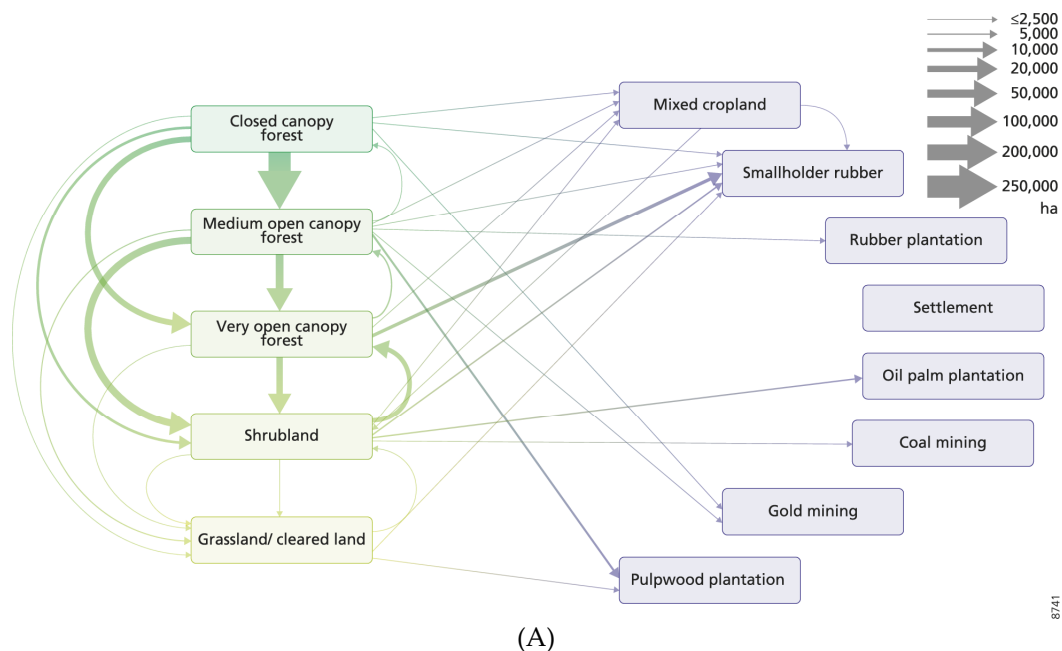


Figure 3. Cont.

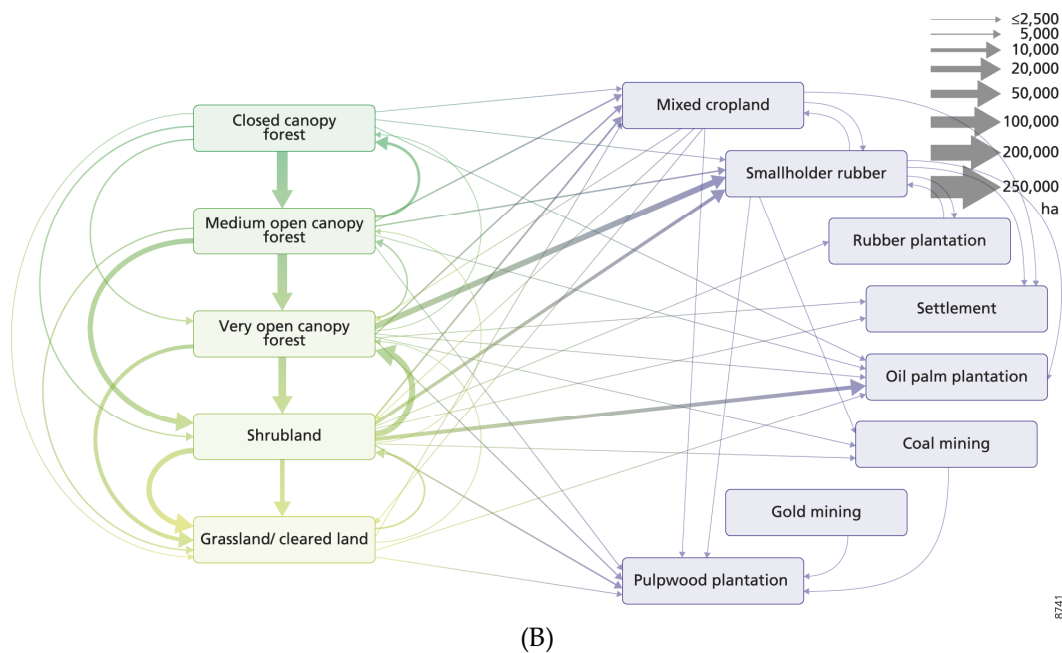


Figure 3. Quantification and schematic presentation of the land cover change processes and trajectories in the West Kutai and Mahakam Ulu districts based on the pixel-to-pixel cross tabulations of the land cover maps and the diagram resulting from the interviews. The boxes on the left indicate the naturally-occurring land cover types and the boxes on the right the agricultural land uses, mining sites and settlements. Each arrow shows the change from one land cover type to another that occurred from 1990–2000 (A) and from 2000–2009 (B). One arrow thus shows a one-step trajectory. The thickness of each arrow (see legend) indicates the area of change for each of the trajectories within the given time period. The land cover changes identified for the entire period of 1990–2009 are shown in Figure S5 (in the Supplementary Materials).

Table 1. Quantified land cover change processes based on remote sensing data [43] that occurred in the periods 1990–2000, 2000–2009 and 1990–2009. See Supplementary Materials S2 for a definition of the land cover change processes.

Land Cover Change Processes	Area (ha)			% of Total Land Cover Change		
	1990–2000	2000–2009	1990–2009	1990–2000	2000–2009	1990–2009
No land cover change	2,758,947	2,677,946	2,270,283			
Total land cover change	534,671	615,672	1,023,335			
Degradation	366,208	305,158	599,005	68	50	59
Deforestation	91,908	114,146	177,969	17	19	17
Land clearance	10	501	405	0	0	0
Regeneration	28,417	60,238	68,070	5	10	7
Conversion of all land cover types to agriculture, mining or settlements	41,648	130,170	168,708	8	21	16
(Conversion of all forest types to agriculture and mining) *	(30,982)	(69,914)	(113,343)	(6)	(11)	(11)
Abandonment and regeneration	1475	2617	1860	0	0	0
Water	5005	1288	6293	1	0	1
Total land area	~3.3 Mha	~3.3 Mha	~3.3 Mha	100	100	100

The percentages are rounded. * Part of ‘Conversion of all land cover types to agriculture, mining or settlements’.

3.3. Mapping of Land Cover Change Processes and Trajectories

We mapped land cover change processes for 1990–2000 (Figure 4A) and 2000–2009 (Figure 4B) to analyze the spatial variation of the land cover change. The matrix of colored pixels has more and smaller clusters in Figure 4B than in Figure 4A, which indicates that land cover change occurred in more different locations and that the processes became more intermixed with one another over time.

For example, forest degradation (yellow pixels) and deforestation (red pixels) were more clustered in the period 1990–2000 than in 2000–2009 (Figure 4A,B).

In Figure 5, we mapped the land cover trajectories related to smallholder rubber and oil palm for the period 1990–2009. The yellow pixels show that most of the smallholder rubber remained unchanged (92% of total smallholder rubber). In turquoise, the loss of smallholder rubber area is shown to have subsequently changed to other land uses (~7% of total smallholder rubber in 1990), such as settlements and oil palm plantations. Dark blue represents the land that was converted from any land cover type to smallholder rubber, which shows the further expansion of this land use.

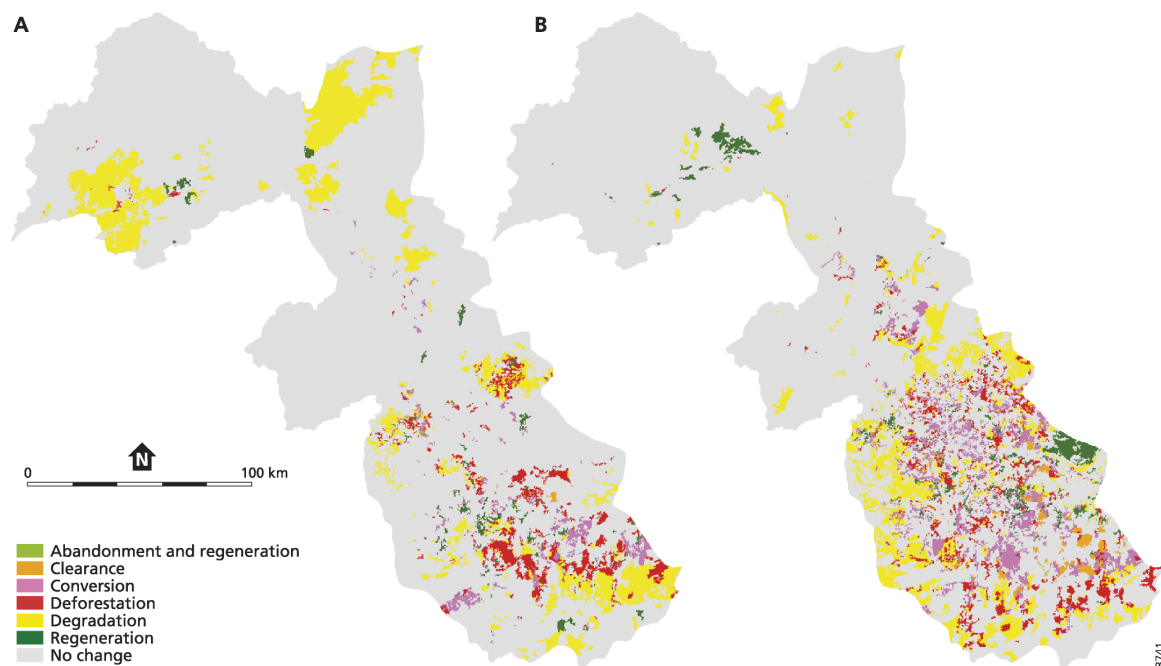


Figure 4. Land cover change processes that occurred in the West Kutai and Mahakam Ulu districts: (A) in the period 1990–2000; and (B) in the period 2000–2009 (one raster cell is 100 m × 100 m).

3.4. Land Cover Change in Concessions and Land Allocation Zones

The results of the overlay of the land cover types and land cover change processes that occurred in the period 2000–2009 with concession types are presented in Tables S9 and S10, respectively. Table S9 shows that 51% of the study area was allocated to timber, logging and oil palm concessions. About 49% of the remaining forests in 2009 were found in concessions, mostly in logging concessions (~1.1 Mha) and oil palm concessions (~144,700 ha) (Table S9). Most of the closed canopy forest was located outside concessions (~72%: 0.8 Mha of total 1.1 Mha). In the logging and oil palm concessions, most of the forest degradation and deforestation also occurred between 2000 and 2009, with 51% and 38% in logging concessions and 11% and 20% in oil palm concessions, respectively (Table S10). Regeneration occurred mostly outside concessions (49–60%, Table S10). About 64% of the oil palm in 2009 was planted within oil palm concessions (~16,600 ha). Additionally, in 2009, only less than 6% of the oil palm concessions were actually planted with oil palm (Table S9). The remaining area in oil palm concessions was covered with forest (~48%), grasslands or shrublands (~33%) and smallholder rubber (9%, Table S9). Smallholder rubber was mostly planted in oil palm (~46%) and logging concessions (~39%), while mixed cropland was evenly spread throughout the three concession types (Table S9). More details are included in Table S9.

Overlaying the 2009 land cover map with the land allocation zoning map demonstrated that the land cover types were generally found in the zones that were designated for these land cover types (Table S11). In 2009, most of the forests were located in the limited production forest zone and

watershed protection forest zone (~50%, Table S11). As expected, most oil palm plantations (82%), smallholder rubber (73%), mixed cropland (69%), coal mining (87%) and rubber plantations (88%) were present in the non-forest zone (Table S11). However, there is some discrepancy between the concession and land allocation zoning data (Table S12). For example, only ~75% of the oil palm concessions were located in the non-forest zone, while ~21% was located in the production forest zone (Table S12). Further, some logging concessions appear to overlap with the conservation forest zone (~3600 ha) and watershed protection forest zone (~27,400 ha). As a result, the protection or conservation of the ecosystems, biodiversity and life support systems for which these zones have been designated is under threat.

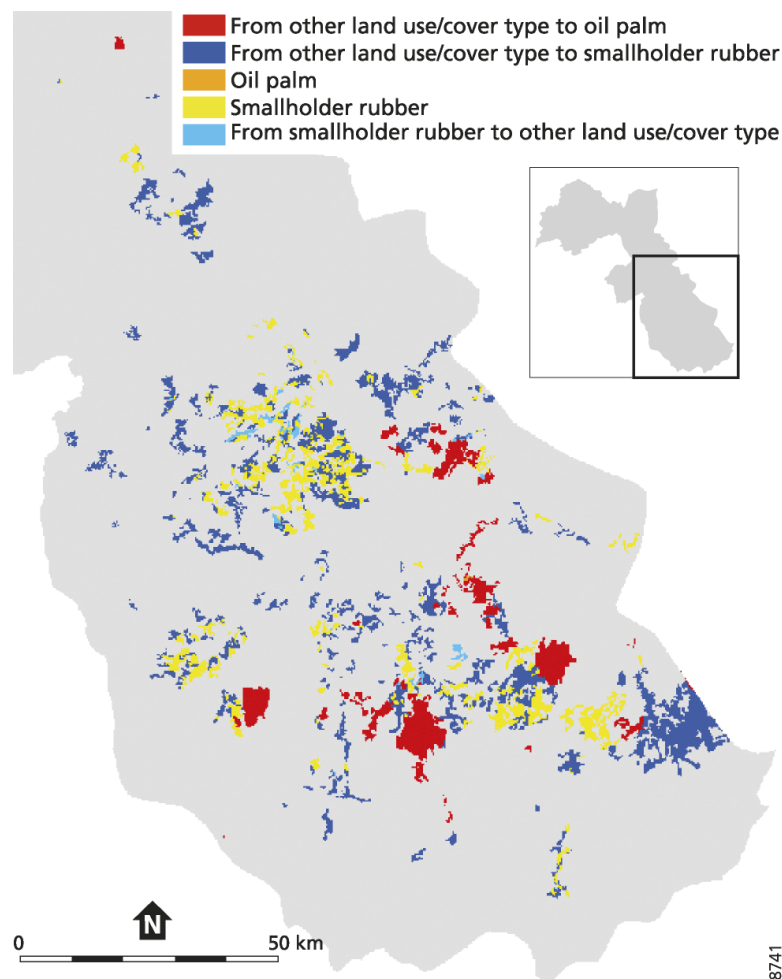


Figure 5. Land cover change trajectories related to smallholder rubber and oil palm mapped for the period 1990–2009 (one raster cell is 100 m × 100 m).

4. Discussion

In this study, we have integrated pixel-to-pixel cross tabulations, land cover (change) mapping and a workshop with experts to generate a more comprehensive analysis of the main land cover change processes and trajectories in a tropical forested landscape. Firstly, our findings show that most of the land cover changes between 1990 and 2009 involved degradation (~59% of total land cover change) and deforestation to grasslands and shrubs (~17%) and to a lesser extent conversions from forest to agriculture and mining (11%). This high presence of forest degradation and deforestation may partly be related to the extensive and recurring El Niño forest fires, such as in 1997–1998 [45]. Further, the combined analyses showed that from 1990–2000 to 2000–2009, a shift occurred from mainly processes of forest degradation, deforestation and the development of small-scale agriculture to an additional increased development of large-scale monocultures. These findings are in line

with the findings of [26,28,46] for the Bungo district in Sumatra and the former West Kutai district. This shift coincided with the Reformasi phase in Indonesia: before 1999, centralized policies were more focused on the establishment of logging concessions and pulpwood plantations, while after 1999, the decentralized policies have had a stronger focus on agricultural expansion [36]. The analyzed districts seem to be in a transition from mostly forest cover and small-scale mixed land uses to predominantly monocultures [6,47], with small-scale mixed land use as an intermediate land cover type [26]. This transition may be driven by multiple factors, including the district, provincial and national governments' interests in profitable cash crop plantations for the production of rubber and palm oil, for example, and local people's responses to economic opportunities [17,48–50]. However, such a transition can also indicate that small-scale farmers and their mixed croplands are being displaced, which can negatively impact their livelihood and local food production [51].

Second, the combination of pixel-to-pixel cross tabulations and expert knowledge showed that the different types of land cover changes in the study area increased and involved a more diverse set of characteristic trajectories in the period 2000–2009, compared to the period 1990–2000. By these combined analyses, we were able to create a shortlist of the main land uses that contributed to land cover change, namely smallholder rubber, pulpwood plantations, mixed cropland and oil palm plantations. This shortlist is similar to the main drivers of forest loss that have been identified in previous studies (e.g., [18,20]). However, instead of ranking these as drivers of land cover change or forest loss [20], we thus found that these land uses had been part of characteristic land cover change processes and trajectories that in some cases (11% of total land cover change) involved more than one step and thus an additional or “intermediate” land cover type. As a result, if the intermediate land uses in these trajectories were not observed during a certain time period, a more stable land use involved could have been misinterpreted as a main driver of forest loss. The information from the workshop with the experts was therefore crucial in understanding the different short-term steps in the trajectories. The series of decadal remote sensing maps, however, did not capture all trajectory steps that had occurred in less than 10 years according to the expert knowledge. Further, neither was it able to support the identification of indirect land cover changes which may have occurred by the interaction of intermediate and more stable land uses. With annual remote sensing-based maps and local on-the-ground data, such analyses can be improved. The quantification and visualization of LULC change processes and trajectories with detailed LULC classes in this study adds to earlier studies on LULC change trajectories [17,26,28].

Fourth, our mapping analyses showed that in the period 2000–2009, most of the forest loss and degradation occurred in logging and oil palm concessions (~60%), which is similar to the estimates for the whole of Kalimantan [20]. In 2009, about 49% of the remaining forests were found in concessions. Furthermore, most of the monoculture plantations and concessions in our study area were developed in the land allocation zones as designated by the government, which is thus in line with the government's spatial planning. This shows that spatial planning can play a substantial role in guiding the expansion of agriculture in more sustainable directions which involves the maintenance of local food production and forests, particularly the large area of forest that still exists in the current concession areas. A method that can support the sustainable development of agriculture and maintenance of forests is the so-called Responsible Cultivation Area method [52]. However, the focus of policy making and spatial planning should not be restricted to the responsible expansion of monoculture plantations. As we found in our study that smallholders played an important role in land cover change, the inclusion of small-scale agricultural development is also important.

The 75% accuracy of the 2009 land cover map points towards a sub-optimal land cover classification, which may lead to a wrong interpretation of the timing of changes or even wrong trajectories. Additionally, expert knowledge can be influenced by the memory of the experts and is therefore subjective. The use of annual remote sensing data could support a more precise classification, as well as the identification of more intermediate steps in the trajectories and the quantification of their spatial and temporal dimensions [32]. Unfortunately, no annual cloud-free optical remote sensing

data were available at a moderate spatial resolution for the study area in the time period analyzed. As a complementary source of information, expert knowledge was used to understand the land cover change processes and trajectories that have occurred between the remote sensing observation years. Because land cover and ecological, social and political conditions are very dynamic in the study area, we recommend more regular and more intensive field data collection in subsequent trajectory analyses, for example on farmers' choices, illegal logging practices, forest fires and immigration. Using such data, the land cover types of mixed cropland and smallholder rubber, which can constitute a mixture of small-scale farming practices, could also be refined.

Our study shows that local to landscape-scale trajectory analyses can provide a more comprehensive view on which land uses are involved in land cover change and forest decline and how these land uses interact with one another. This is particularly important for spatial planning in tropical landscapes where agriculture develops rapidly [24–29]. With the growing global demand for rubber and palm oil, and the higher returns of these cash crops for small-scale farmers, more conversions from small-scale mixed land uses to monocultures are expected. Conversions into cash crops can be identified and monitored by such trajectory analyses, and subsequently, zoning, conservation and moratorium policies can be developed to help steer such changes into more sustainable directions. This is important since such land intensifications can change the socio-cultural character of the landscape, impact local food production and result in declined levels of biodiversity [26,47,53,54] and carbon stocks [55]. Involving communities in the spatial planning process is recommended, as they may play an important role in land cover change and may be affected by it. If forest landscapes are to be maintained, maintenance of forests and small-scale mixed land uses needs to be incentivized, for example by REDD+ or through subsidies for local food production.

5. Conclusions

This study aimed to present an integrated approach, combining land cover (change) map analyses and expert knowledge to characterize and map land cover change processes and trajectories that have contributed to forest loss, forest degradation and displacement of mixed croplands at the local to landscape scale. Pixel-to-pixel cross tabulations, spatial analyses and expert knowledge enabled a comprehensive estimate of the land cover change trajectories and processes that contributed to forest cover loss and degradation in the West Kutai and Mahakam Ulu districts in the Indonesian province of East Kalimantan. This approach is useful for application in other tropical forest areas where large-scale agricultural developments are taking place or expected to take place. Particularly in areas where no annual remote sensing data are available, the integration of satellite-based maps and expert knowledge can be of great importance.

Our results show that the land cover of about one-third of the study area changed in the period 1990–2009, with a decrease in forest area of almost 10%. Based on our quantitative and spatial analyses, forest degradation and deforestation to shrubs and grasslands were found to be the dominant land cover change processes causing declining forest cover and quality. Additionally, the combination of the pixel-to-pixel cross tabulations and expert knowledge showed that the different types of land cover changes in the study area increased and involved a more diverse set of characteristic trajectories in the period 2000–2009, compared to the period 1990–2000. Between 1990 and 2009, about 89% of the total area of land cover change changed through one-step trajectories and 11% by two-step trajectories, and most trajectories involved degradation and deforestation processes. Deforestation to grasslands and shrubs increased between 1990 and 2009 and entailed a total land area of ~92,000 ha in 1990–2000 and ~114,000 ha in 2000–2009, which is about 17% and 19% of the total land cover change area in these time periods, respectively. However, degradation decreased from 68% of the total land cover change in the period 1990–2000 to 50% in 2000–2009. Conversion from forest to agriculture and mining increased from 6% in 1990–2000 to 11% between these two time periods. Further, conversions from forest types to small-scale agriculture, such as mixed cropland and smallholder rubber, occurred more frequently than conversions to large-scale monocultures,

such as oil palm or pulpwood, although conversions to large-scale monocultures increased over time. The integrated trajectory analyses showed that land cover change occurred in mostly one-step trajectories of degradation and deforestation; multiple-step trajectories from forest to grassland and further to large-scale monocultures; and multiple-step trajectories from forest to small-scale mixed land uses, to smallholder rubber and sometimes further to monocultures, mostly oil palm. By these trajectories, we show important interlinkages between small-scale and large-scale agriculture, and we thereby conclude that not only forests are vulnerable to conversion, but also small-scale mixed land uses. It is important to further understand and account for such interlinkages and processes of change in order to guide potential land use intensification in more sustainable directions, while maintaining local food production. Further, land cover change follows (at least partly) concession and land allocation zoning policies and, as a result, spatial planning can thus play a substantial role in guiding the expansion of agriculture in more sustainable directions, which involves the maintenance of forest cover and local food production.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2073-445X/7/3/108/s1>: Supplementary Materials S1. Expert group-consensus workshop. Supplementary Materials S2. Land cover change processes and trajectories. Figure S1. Conceptual model of the land cover changes and land cover change processes in a disturbed tropical forest landscape (processes are indicated by a single arrow; trajectories can involve one or multiple arrows). Figure S2. Land cover maps of the West Kutai and Mahakam Ulu Districts for 1990 (A), 2000 (B) and 2009 (C) (following [43]) (one raster cell is 100 × 100 m). Figure S3. (A) Land allocation zones; (B) altitude (m) overlaid with concession maps for the West Kutai and Mahakam Ulu Districts (source: World Resources Institute 2014). Table S1. Specification of the selected land cover types (following [43]). Table S2. Absolute land area (ha) per land cover type and relative land cover changes (%) between 1990, 2000 and 2009. Figure S4. The main land cover change processes and trajectories identified for West Kutai and Mahakam Ulu based on expert knowledge. The trajectories are either dominant (thick arrows) or less dominant (thin arrows): (A) degradation and/or deforestation to grasslands or shrublands; (B) deforestation to grasslands and conversion from grasslands to large-scale plantations; (C1) degradation and/or deforestation to grasslands, conversion from grasslands to mixed cropland (which the experts referred to as shifting cultivation areas and/or dryland rice fields), after a few years, conversion from mixed cropland to smallholder rubber and, in certain cases, (C2) further conversion from smallholder rubber to stable land cover types, such as oil palm. Table S3. Land cover change matrix (in ha) 1990–2000 for the West Kutai and Mahakam Ulu districts. These matrices indicate the number of pixels change (and thus the hectares) from one land cover type (vertical axis) to another (horizontal axis) within the selected time period. Table S4. Land cover change matrix (in %) 1990–2000 for the West Kutai and Mahakam Ulu districts. These matrices indicate the percentage of pixels change from one land cover type (vertical axis) to another (horizontal axis) within the selected time period. Table S5. Land cover change matrix (in ha) 2000–2009 for the West Kutai and Mahakam Ulu districts. These matrices indicate the number of pixels (and thus the hectares) change from one land cover type (vertical axis) to another (horizontal axis) within the selected time period. Table S6. Land cover change matrix (in %) 2000–2009 for the West Kutai and Mahakam Ulu districts. These matrices indicate the number of pixels change from one land cover type (vertical axis) to another (horizontal axis) within the selected time period. Table S7. Land cover change processes defined, i.e., the conversions from land cover types in the left columns to land cover types in the top rows. Table S8. Overview of net area lost in 1990 and net area gained in 2009 per land cover type (in hectares). Figure S5. The land cover change trajectories (single arrows) as identified in the West Kutai and Mahakam Ulu districts between 1990 and 2009. Table S9. Land area (hectares) of land cover types in concessions in 2009. Table S10. Occurrence (%) of land cover change processes between 2000 and 2009 in concession types. Table S11. Occurrence of land cover types (in 2009) in land allocation zones [56] (in hectares). Table S12. Occurrence of timber, logging and oil palm concessions in land allocation zones [56].

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